PRETTY: Grazing altimetry measurements based on the interferometric method

Høeg, Per; Fragner, Heinrich; Dielacher, Andreas ; Zangerl, Franz ; Koudelka, Otto ; Høeg, Per; Beck, Peter ; Wickert, Jens

Published in:
Proceedings of the 5th Workshop on Advanced RF Sensors and Remote Sensing Instruments, ARSI'17

Publication date:
2017

Document Version
Peer reviewed version

PRETTY: Grazing altimetry measurements based on the interferometric method

Heinrich Fragner[(1)], Andreas Dielacher[(1)], Franz Zangerl[(1)], Otto Koudelka[(2)], Per Høeg[(3)], Peter Beck[(4)], Jens Wickert[(5)]

[(1)]RUAG Space GmbH, Stachegasse 13, 1120 Vienna, Austria
Email: heinrich.fragner@ruag.com, andreas.dielacher@ruag.com, franz.zangerl@ruag.com

[(2)]Graz University of Technology, Inffeldgasse 12, 8010 Graz, Austria
Email: koudelka@tugraz,at

[(3)]Technical University of Denmark, DTU Space, Elektrovej, Building 328, 2800 Kongens Lyngby, Denmark
Email: per.hoeg@dtu.dk

[(4)]Seibersdorf Labor GmbH, Forschungszentrum Seibersdorf, 2444 Seibersdorf, Austria
Email: peter.beck@seibersdorf-laboratories.at

[(5)]Technische Universität Berlin, German Research Centre for Geosciences GFZ, Germany
Email: wickert@gfz-potsdam.de

ABSTRACT

The exploitation of signals stemming from global navigation systems for passive bistatic radar applications has been proposed and implemented within numerous studies. The fact that such missions do not rely on high power amplifiers and that the need of high gain antennas with large geometrical dimensions can be avoided, makes them suitable for small satellite missions. Applications where a continuous high coverage is needed, as for example disaster warning, have the demand for a large number of satellites in orbit, which in turn requires small and relatively low cost satellites.

The proposed PRETTY (Passive Reflectometry and Dosimetry) mission includes a demonstrator payload for passive reflectometry and scatterometry focusing on very low incidence angles whereby the direct and reflected signal will be received via the same antenna. The correlation of both signals will be done by a specific FPGA based hardware implementation. The demonstration of a passive reflectometer without the use of local code replica implicitly shows that also signals of unknown data modulation can be exploited for such a purpose.

The PRETTY mission is proposed by an Austrian consortium with RUAG GmbH as prime contractor, relying on the results from a previous CubeSat mission (OPS-SAT) conducted by TU Graz under ESA contract [18]. Within the present paper we will describe the architecture of the passive reflectometer payload within this 3U CubeSat mission and discuss operational routines and constraints to be elaborated in the frame of the proposed activity.

OVERVIEW

The main purpose of the reflectometer payload onboard PRETTY is to demonstrate the technical feasibility of the phase altimetric (or phase delay altimetry) approach at grazing incidence angles, which was demonstrated initially using GPS radio occultation data [1]. These observations were achieved with low-gain antennas and state-of-the-art GPS radio occultation receivers without any specific optimization for GNSS reflectometry. A case study of phase data from CHAMP also presented an altimetric retrieval over the Greenland ice sheet and sea ice [2]. The derived surface heights had 0.7 m precision in 0.2 second averaging (1 km resolution). Recently this approach was also proposed within new spaceborne GNSS Reflectometry experiments, as, e.g., GEROS-ISS or G-TERN [3,4] for ocean and ice remote sensing, including surface altimetry. Phase altimetric simulations have been performed for ocean applications within the GEROS-ISS related scientific study GARCA [1, 5]. The simulation results show that phase altimetric retrievals are sensitive to anomalies of the ocean topography and that an altimetric precision of 10 cm in 1 second observation is possible in this respect [6]. Similar precision was demonstrated with airborne experiments [7,8]. An Observation System Simulation Experiment (OSSE) indicated the large potential of future phase delay GNSS-R data to significantly improve ocean modelling and forecast systems [9]. In addition to the ocean applications, especially the G-TERN mission [4] proposed several innovative scientific GNSS-R applications using the phase delay altimetry with special focus to the cryosphere.

The goal of the PRETTY mission is to deliver correlation results from real grazing altimetry measurements to further assess the technical fessibility of this promising GNSS-R observation technique. The measurement data and in particular the noise figures obtained from the measurements will validate the models used for the prognosis of the grazing reflections. The evaluation of this data shall show the usability of this measurement method for earth observation. The absolute accuracy of the altimetry results is not a primary mission goal, since platform components like a POD (precise orbit determination) receiver which would be necessary to meet such a goal are not present on the platform.

The proposed satellite platform for the mission is based on the OPS-SAT architecture which is prepared to accommodate the signal processing part of the proposed PRETTY mission. The necessary HW modifications to implement the complete passive reflectometer are mainly related to the addition of a suitable antenna.

The non-recurring engineering effort to implement the passive reflectometer is thus to a large extend driven by the necessary SW and firmware development. This work is based on previous developments and studywork, in particular the signal processing core PACO has been developed within an ESA project [10]. This core is intended to be used also for the phase delay altimetry measurements of the ESA mission GEROS-ISS [3], which recently finished it's Phase A.

The PRETTY mission will also host a radiation dosimeter which will allow insight into the actually applied radiation environment and to correlate the radiation figures with the operational performance of the primary payload. This payload requires also additional hardware compared to the OPS-SAT heritage design. [19,20]

The mission will be based on a 3U CubeSat with double deployable solar panels. The spacecraft front and rear view is shown in Fig. 1.

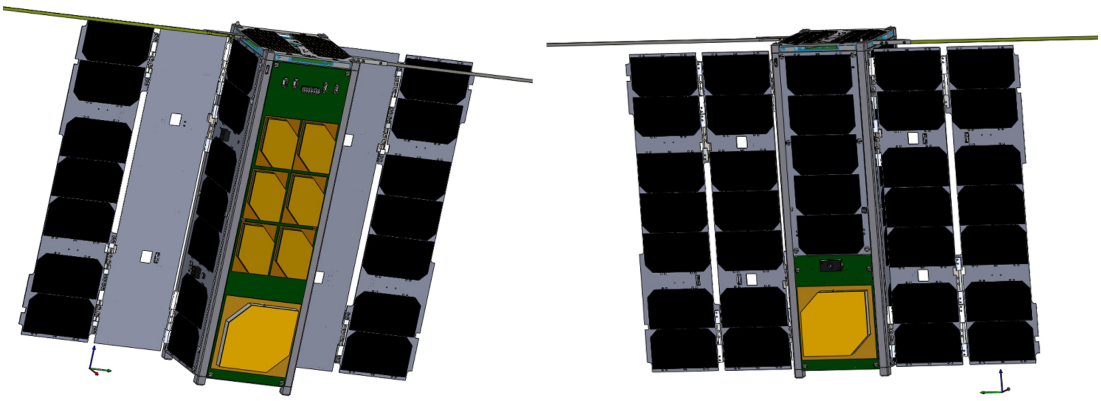

Fig. 1 – Spacecraft front and rear view (red: x, green: y and blue arrow: z direction)

The rear of the deployable panels (shown on the right) is fully covered with solar cells. Along with the body mounted panels on the –X face this configuration provides 32 solar cells for meeting the power requirements of the mission. The spacecraft is also equipped with further solar cells on the opposite side of the spacecraft including the Y faces and the +Z face of the satellite body, allowing the spacecraft to generate sufficient power in every orientation.

The baseline system architecture is shown in Fig. 2 as common for Cubesats it is strongly based on the use of COTS (commercial of the shelf) components for the satellite bus to provide the basic mission capabilities.

The payloads with a high performance processing platform are the satellite experimental processing payload (SEPP) processor connected with a software-defined radio front-end for the passive reflectometry. This module has been developed by TU Graz in the frame of the OPS-SAT mission and will undergo a redesign in the frame of the PRETTY development phase.

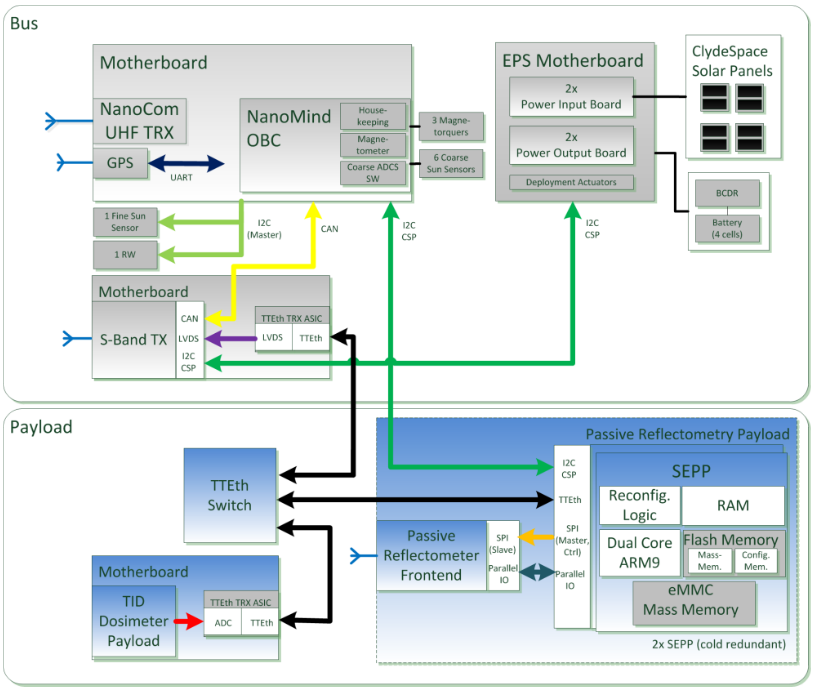

Fig. 2 – PRETTY system architecture Remove TTT

Payload OBC

The SEPP is realized on a very compact PCB (printed circuit board) design with optimal form factor for CubeSat and Nanosatellite missions. Outstanding computational power is achieved by the use of an Altera Cyclone V SX System-on-Chip (SoC) digital logic device with a built-in dual core ARM A-9 CPU with 800 MHz clock rate and a Cyclone V Field Programmable Gate Array (FPGA).

All Altera SoC SX devices consist of an internal HPS (Hard Processing System) and a FPGA (Field Programmable Gate Array) part. The Altera Cyclone V SX SoC HPS is a fully functional computer and contains a dual core ARM CPU with several built-in hardware blocks and device interfaces. It is also worth mentioning that the Altera Cyclone V SX SoC benefit from the availability of built-in ECC (error correction coding) features.

Both, HPS and FPGA are connected to several built-in peripheral hardware controllers and allow the implementation of a powerful system. A fast DDR3L RAM (random access memory) with 1 GByte enables the execution of high-end software applications as needed for the computational intense mission SW. By default the SEPP platform is equipped with a Linux Operating System and several Linux drivers and additional user space software stored on the embedded Multi-Media Controller (eMMC) flash memory. With 16 GBytes, the eMMC provides sufficient capabilities for data storage required by the mission.

To connect the SEPP FPGA directly with the RF front end the SEPP board provides a general purpose 14-bit interface for parallel data transfer of signal samples.

The SEPP will host the mission specific SW which is responsible to setup the correlators for the direct and reflected beam. For this purpose the integration times, the expected relative delay of the two signals as a function over time and the according antenna orientation (and hence the spacecraft orientation) have to be defined by the on board SW. After such an observation event the resulting data will be stored in an on board mass based on SD card before sending it to ground when the PRETTY satellite enters the field of view of the ground station.

The SEPP mechanical design features customized aluminium housing. This housing gives additional protection against radiation and provides sufficient area and volume for thermal management. The housing is designed for CubeSat and Nano-Satellite missions and allows a mechanically stable combination of several SEPP boards to a cold redundant module. On top and bottom of the SEPP module with two units in cold redundancy a custom PCB can be attached which allows the connection of the SEPP stack to a different bus connector, e.g. PC104.

Passive Reflectometry Front End

The baseline SDR (Software-defined radio) front end for the passive reflectometer payload is the Myriad RF-1 COTS design. The Myriad–RF 1 board is a multi-band, multi-standard RF module, based on the state of the art LMS6002D transceiver IC by Lime Microsystems. It has one RF broadband output, one RF broadband input with digital baseband interface, established via standard connector FX10A-80P. The board also provides the user with pin headers for power supply, reference clock, analogue I/Q input/output and SPI interface connections. It contains everything needed for it to be connected to baseband (BB) chipsets, FPGAs or to run in standalone mode. This module underwent successful radiation tests at ESTEC.

The chip is a transceiver with continuous coverage of the 300 MHz to 3.8GHz frequency range, with a programmable RF modulation bandwidth up to 28 MHz, which has to be divided by 2 because a single received sample is converted to a pair of I and Q samples, yielding effectively a baseband bandwidth of 28 MHz. This is sufficient to fulfil the required bandwidth of 14MHz maximum for operating the passive reflectometry experiment.

For the mission, only the receiver part of the LMS6002D will be used. The receiver part is equipped internally with three independent and selectable LNAs. One of the three available LNAs will be used to amplify the incoming signal and to connect it with the internal demodulator, providing an internal max receive gain of 78dB. In addition, an external Low Noise Amplifier (LNA) will be used to further increase the gain to ~98dB. The antenna input is passed via an optional filter to the LNA.

The SDR front-end is embedded into a custom adapter board developed by TU Graz (SDR Routing PCB) which connects the PC104 stack of the satellite bus with the payloads.

The proposed antenna solution is an array of 6 patches which will be integrated in the +X body mounted solar panel. This kind of patch antenna was specifically designed by TU Graz for this application and the simulations of this arrangement yields an antenna gain of 15.1 dBi and a half-power beamwidth of 25.5°. The bandwidth is around 70 MHz at the L1 band. The antenna pattern is depicted in Fig. 3.

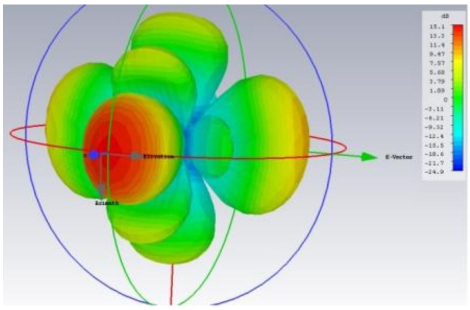
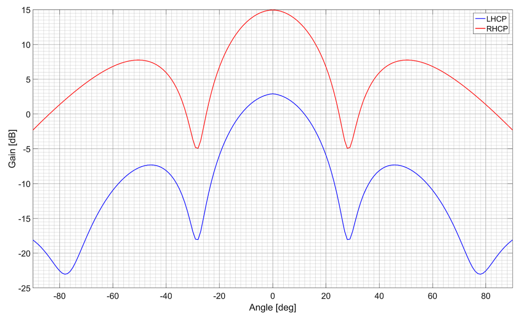

Fig. 3 – Passive reflectometer antenna pattern, 1.573GHz

PASSIVE REFLECTOMETRY SYSTEM DESCRIPTION

Visibility analysis:
In order to determine the number of grazing reflection points available, an orbit simulator has been designed. The model used has been verified by simulation and gives sufficiently accurate numbers for the purpose of the visibility analysis. The model calculates for an arbitrary orbit (determined by TLE elements from NORAD) the ground track, coordinates (x, y, z and lat, lon, height), visibility times over the ground station and distance between the PRETTY satellite and all GPS satellites.

The same model is also used to determine the visibility of the ground station. This analysis shows that during a complete day the PRETTY satellite will be visible about 6 times for 5 to 10 minutes. Assuming a 550 km SSO orbit and a downlink data rate of 2 Mbit/s, the average contact time per day is about 37 minutes, leading to a maximum downlink data volume of 555 MB per day.

The orbit simulator is also capable to calculate the reflection points on earth. Using this model, the reflection points for all GPS satellites have been calculated (grazing and non-grazing). When restricting the simulation time to 1 hour (in order not overload the plot) and considering the available reflection points, this leads to Fig. 5 which clearly shows that there is a high coverage, even for grazing altimetry over sea.

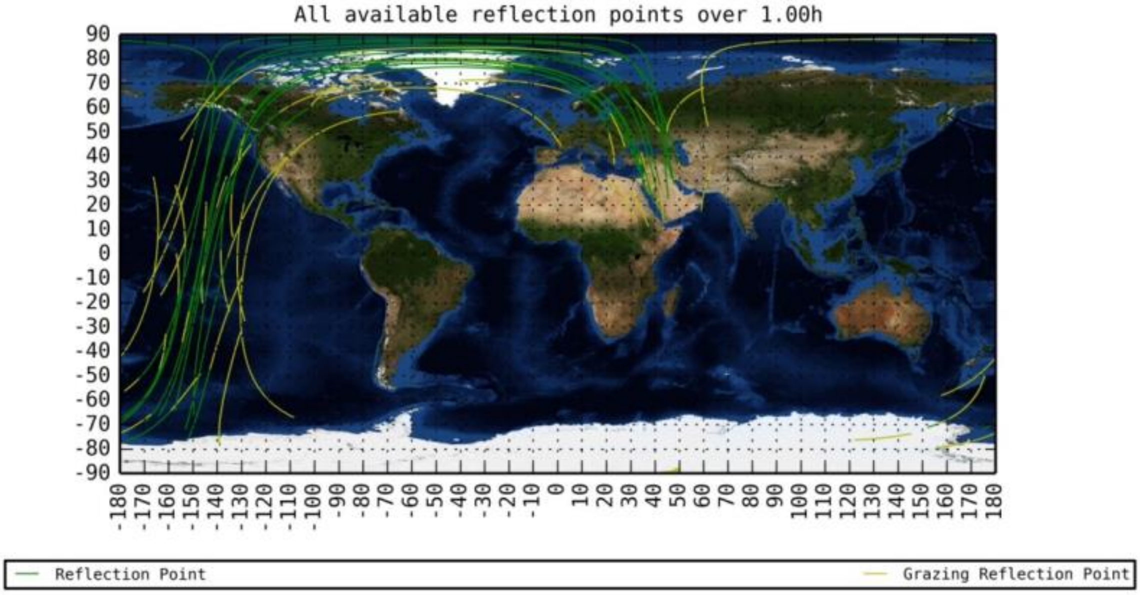

Fig. 51 –Reflection points within one hour

Reflectometer Link Budget

The link budget determines the signal to noise ratio (SNR) of the measurements available for altimetric estimates. For the interferometric correlation approach, also the link budget for the direct signal has to be assessed, as the loss with respect to correlation of the reflected signal with a clean replica is indirectly proportional to the direct signal at the input of the correlator.

The SNR of the direct signal mainly depends on the transmitted GNSS signal power, the free space loss, ionosphere and troposphere delay and divergence, transmitter and receiver clock offsets, and receiver features such as receiver antenna gain and front-end noise figure [11]. The ray bending of the transmitted GNSS signal depends primarily on the ionospheric level of disturbance, the elevation angle at the centre of the elliptical reflection region, and the humidity variations in the ocean boundary layer [11] [12]. The ionosphere miss distance at the receiver can be up 800 meters during severe disturbed conditions [11]. Normally this may lead to slow spectral changes during the cause of the observations. While the ocean roughness may expand the reflection zone from one kilometre to tens of kilometres as function of the reflection angle of the receiver at the reflection zone leading to significantly SNR changes during strong ocean winds and waves [13].

In addition, the reflected signal is affected by attenuation in the ionosphere and the atmosphere [11], the amount of reflected energy and the scattering of the electro-magnetic wave of the Earth's surface (i.e. signal variations due to wave form shape distortions caused by sea surface roughness, ocean waves and wind) [13]. For the proposed instrument, only the RHCP contribution of the reflected signal can be considered.

Using the assumed orbit height of the PRETTY satellite the angle between the GPS satellite and PRETTY has been calculated to be at most 15.3 degree. At these angles there is still a relatively large power emitted from the antennas of the GPS SVs. The transmit antenna of the GPS satellites has a nearly constant gain up to 15 degrees, with a falloff of about 20dB per 20 degree [16, Fig 12]. For the calculation of the GPS transmit power, a transmit antenna gain of -0.46dB has been assumed.

The established link budget model which takes into account various gain/loss components such as the GPS transmit gain, atmospheric loss, reflection loss, etc. shows that the available power for the direct and reflected signal is between -174.84 dBW and -155.69 dBW for the L1 frequency band.

Considering the antenna gain of about 15dB, the external LNA and the front-end gain, the signal power after the front-end is about -90dBm with an SNR between -20.18dB and -1.02 dB (assumed 400K noise temperature and 2MHz bandwidth). Furthermore, the gain due to the correlation with 50ms coherent integration time, leads to a SNR on the correlator output between 24.21 dB and 42.00 dB. These values are compatible with the proposed grazing altimetry mission and will allow precise measurements. For phase-based altimetry, these SNR values correspond to an average phase error of about 3.6° and 0.45°, respectively.

Data Rates

The telemetry downlink data rates required for the passive reflectometer can be arbitrarily high, and are determined due to the combination of the coherent and incoherent integration times. In [17] it is stated that the coherent integration for grazing altimetry can be up to 50ms. Considering the maximum PACO coherent integration time of 10ms, combined with 5 incoherent integrations (note that the PACO can integrate complex or power waveforms) we can reach the suggested 50ms. Assuming the unrealistic case, that there will always be a measurement possible, this would lead to a rather high data rate for the downlink, since the PACO has for each measurement 5*200 results, each with 32 bit, leading to 5*6.4kbit*20 = 640kbit per second, or 80kB/s. Although there would be enough storage on the PRETTY, the downlink data rate and the visibility do not allow transmitting all the data. Considering the minimum downlink rate of 1.8Gbit per day and the maximum data generated by the PACO of about 55 Gbit/day (one measurement every 50ms, no compression, 100% duty cycle), it is clear that there is the need for data reduction. However, the measurements will not be done with a 100% duty cycle and the integration times will be increased as well. We assume that a realistic duty cycle will be around 1/8th of the available time to be a viable measurement time, whereas the integration times will be more in the range of 200ms to 1s, hence reducing the generated data by at least a factor of 32.

Operational Concept

The proposed concept of operation is such that there will be an on-ground calculation of the reflection points. These reflection points will then be pre-selected to the ones which are the most promising for the measurements. For these selected measurements, the pre-processing on ground generates a dataset to be uploaded, including the pre-calculated positions of the PRETTY, GPS satellite and reflection point, the time stamp when to perform the measurement and some additional parameters. After upload to the PRETTY satellite, the payload software checks the incoming data and compares it to the actual on-board position data, and takes these inputs as initial values of the reflection point.

On board the spacecraft the reflection point will be recalculated with the actual position and ephemeris data from the GNSS SV to obtain a sufficient accuracy of the reflection point. During the Phase B study of the planned mission it will be verified if the accuracy of the on-board calculated reflection point lies within the limits of the correlation window, or if the payload software needs to implement a peak-search algorithm.

The measurements are stored inside the payload in a data package, which also holds the exact timestamp of the measurement start, PACO configuration values (e.g. used Doppler frequency) and the assumed positions. This is needed for the ground processing to accurately map the acquired data to the earth surface.

PRELIMINARY SYSTEM ANALYSIS

Mass analysis

A preliminary mass budget for the satellite has been calculated including unit level margins between 5% and 20% according to the ECSS definition as well as a system level margin of 20%. The mass budget result shows that the satellite fits in the 6 kg envelope stated by most of the 3U CubeSat deployers.

Pointing profiles

As the antenna half-power beamwidth is 25.5°, there are no demanding pointing accuracy requirements. The proposed system with a pointing accuracy of 5° is suitable to operate the mission.

Power analysis

The proposed satellite configuration with double deployable solar panels provides 32 solar cells exposed to the sun with a maximum power generation of almost 1W each (BoL, sun vector orientation normal to the solar cell).

The preliminary power analysis shows that for unrestricted payload operation 16.3 W are required. This can be achieved with an SSO LTDN of 06:00 during the sunlight season. As a compromise, a minimum duty cycle of 1/3 of the orbit for operation of the main passive reflectometer payload has been considered. This duty cycle is achievable with an SSO with LTDN of 09:00. Thus SSO LTDNs between 06:00 and 09:00 are required to provide sufficient power capabilities for the mission, where LTDNs closer to 06:00 are preferred.

Telemetry data rate analysis

A preliminary data-rate requirement analysis was performed, based on the estimated daily collected data volumes and the available daily contact times of the satellite with the ground station in Graz for an SSO with 550 km altitude. The analysis results show that the mission can be operated with the envisaged single ground station in Graz. The downlink data rate requirement for optimal mission operation is 2 Mbit/s. with a comfortable link margin of 5.7 dB.

[1]Beyerle, G., and K. Hocke, Observation and simulation of direct and reflected GPS signals in radio occultation experiments, Geophysical Research Letters, 28, 9, pp. 1895-1898, 2001.
[2]Cardellach, E., C.O. Ao, M. de la Torre-Juárez, and G.A. Hajj, Carrier phase delay altimetry with GPS-reflection/occultation interferometry from Low Earth Orbiters, Geophys. Res. Letters, Vol. 31, No. 10, L10402, May 2004.
[3] J. Wickert, et al, "GEROS-ISS: GNSS Reflectometry, Radio Occultation, and Scatterometry Onboard the International Space Station" IEEE Journal of selected topics in applied earth sciences and remote sensing, Vol. 9, No. 10, pp. 4552-4580, October 2016
[4] J. Wickert/E. Cardellach et al., „G-TERN: GNSS Transpolar Earth Reflectometry ExploriNg System" Proposal for ESA Earth Explorer Call 9, Barcelona/Potsdam, June 2017.
[5] GARCA, GNSS-R assessment of requirements and consolidation of retrieval algorithms, Final Project Report, ESA-AO1-7850/14-GARCA-FR, pp 463, 2016.
[6] A.M. Semmling, V. Leister, J. Saynisch, F. Zus, S. Heise, J. Wickert, „A Phase-Altimetric Simulator: Studying the Sensitivity of Earth-Reflected GNSS Signals to Ocean Topography" IEEE Transactions on Geoscience and remote sensing, Vol. 54, No. 11, pp. 6791-6802, November 2016
[7] A. M. Semmling, J. Beckheinrich, J. Wickert, G. Beyerle, S. Schön, F. Fabra, H. Pflug, K. He, J. Schwabe, and M. Scheinert, „Sea surface topography retrieved from GNSS reflectometry phase data of the GEOHALO flight mission" GeophysicalResearchLetters 10.1002/2013GL058725
[8] A. M. Semmling, J. Wickert, S. Schön, R. Stosius, M. Markgraf, T. Gerber, M. Ge, G. Beyerle „A zeppelin experiment to study airborne altimetry using specular Global Navigation Satellite System reflections" Radio Science, VOL. 48, 1‑14, doi:10.1002/rds.20049, 2013
[9] J. Saynisch, M. Semmling, J. Wickert, M. Thomas, „Potential of space-borne GNSS reflectometry to constrain simulations of the ocean circulation"Ocean Dynamics (2015) 65:1441‑1460
[10] A. Dielacher, H. Fragner, „PARISCorrelator Final Report" P-11281-RP-0006-RSA, 30 Jan 2015
[11] P. Høeg et al., "Derivation of Atmospheric Properties Using a Radio Occultation Technique", Sci. Rep., DMI, 95-4, 1995.
[12] P. Høeg, R. Prasad, and K. Borre, "Impact of Atmosphere Turbulence on Satellite Navigation Signals", in Satellite Communications and Navigation Systems, E. Del Re, and M. Ruggieri (Eds.), Springer Verlag, 2008.
[13] P. Høeg, "Ocean Reflected GPS Signals", Proc., Int. Conf. on Wireless Communications, Vehicular Technology, Information Theory, Aerospace and Electronic Systems Technology, Wireless VITAE, 2009.
[14] A.M. Semmling et al., "A phase-altimetric simulator: Studying the sensitivity of Earth-reflected GNSS signals to ocean topography," IEEE Trans. Geosci. Remote Sens., vol. 54, no. 11, pp. 6791–6802, Nov. 2016.
[15] J. Wickert et al., 'GEROS-ISS: GNSS Reflectometry, Radio Occultation and Scatterometry onboard the International Space Station', IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 9, no. 10, pp. 4552-4581, 2016.
[16] C. Wang, R. A. Walker, M. P. Moody, "A GPS Signal Transmission Model for improved Single Antenna Attitude Determination", MP Moody - 2005 - eprints.qut.edu.au
[17] Manuel Martín-Neira, Weiqiang Li, Ana Andrés-Beivide, Xabier Ballesteros-Sels, "Cookie: A Satellite Concept for GNSS Remote Sensing Constellations IEEE JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATIONS AND REMOTE SENSING, VOL. 9, NO. 10, OCTOBER 2016 4593
[18] Koudelka, O., D.Evans, The OPS-SAT Nanosatellite Mission- A Flexible Platform for On-Board Experiments, 11th IAA Symposium on Small Satellites for Earth Observation, Berlin, 2017.
[19] P. Beck, M. Latocha, M. Wind, Space Radiation Environment Phase-A Study Report Austrian CubeSat Mission (PRETTY), SL-LD-002/17, 2017.
[20] L. Dusseau, Radiation Hardness Assurance and CubeSat: A new Approach for a "New Space", RADHARD Symposium 2017, 16. May 2017, Seibersdorf, Austria. www.radhard.eu.